Shallow Junction Formation by Polyatomic Cluster Ion Implantation

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Abstract —— Recent integrated circuits require shallow junctions which are less than 0.1μm depth. This creates a strong demand for low energy ion beam techniques. Equivalent low-energy and high-current ion beams can be realized quite easily with clusters, because the kinetic energy of the cluster is shared between the constituent atoms. Additionally, cluster-ion beams avoid damage due to excessive charge. We have used polyatomic clusters, decaborane ($B_{10}H_{14}$), as a kind of B cluster, in order to form a very shallow p^+ junction. A B SIMS profile of $B_{10}H_{14}$ implanted into Si (100) at 20keV was quite similar to that of B implanted at 2keV. These SIMS measurements revealed that the cluster ion beam can realize equivalent low-energy implantation quite easily. The implantation efficiency achieved was about 90%. The damage induced by $B_{10}H_{14}$ implantation was completely removed by a 600 °C furnace anneal for 30 min, and implanted B atoms were electrically activated. After rapid thermal annealing (RTA) at 900 °C of a sample prepared with a dose of 5×10^{13} ion/cm^2, the sheet resistance decreased to about 600W/sq. and the activation efficiency was about 50%. These results show that a polyatomic cluster ion beam is useful for shallow junction formation.

I. Introduction

The scaling-down of silicon devices requires good control over the formation of ultra-shallow junctions. Much effort has gone into developing low energy ion beam implanters to overcome space-charge effects [1]. Cluster-ion implantation has two major advantages for shallow junction formation. One is that the equivalent energy effect of a cluster ion is low [2-3]. A few tens of keV cluster, with the size of a hundred atoms, has a few hundred eV in each constituent atom. It is quite easy to obtain equivalent low-energy and high-current ion beams by using cluster ions. Shallow implantation can be realized with a higher energy cluster beam [4]. In addition, a heavily doped layer can be obtained with low cluster ion dose, because one cluster ion contains many atoms. This helps to eliminate charging problems, which occur during high dose ion implantation with conventional ion beams.

The other advantage is the unique type of defect formation resulting from local energy deposition and multiple collisions. It has been reported that defects have a great effect on boron diffusion into Si [5-6]. Molecular-dynamics calculation and experimental results show that the cluster size has a great influence on the number of defects and their distribution, which could not be changed by monomer ion implantation [7]. Therefore, cluster ion implantation techniques have a capability to suppress radiation enhanced diffusion, which is a significant problem in the formation of shallow junctions. A local amorphous region is formed in front of the cluster during penetration into solid. This phenomena can be used profitably to suppress channeling, which is unavoidable with low energy monomer ion beams. In the case of cluster ion implantation, no channeling occurs, since an amorphous layer is automatically formed. Thus, many problems of conventional ion implantation, such as the space-charge effect, transient diffusion and channeling, can be overcome by cluster ion implantation.

Polyatomic molecular ions have similar properties to cluster ions. BF_2 ions are often used in boron implantation. Low energy ion implantation can be realized by using much larger borane molecules. A decaborane ($B_{10}H_{14}$; 99.7 °C melting point; 213 °C boiling point at 1 atm) ion has a similar advantage to that of a cluster ion with the size of ten, because one decaborane molecule contains 10 boron atoms. Furthermore, decaborane is suitable as a source material, because it is solid and safer than diborane (B_2H_6) at room temperature. In this paper, the characteristics of cluster ion implantation with decaborane are investigated and the advantages of it for ultra shallow junction formation are discussed.

II. Experimental

Fig.1 shows the structure of $B_{10}H_{14}$. It is solid and nontoxic at room temperature. Fig.2 shows a schematic diagram of a $B_{10}H_{14}$ implanter. The sublimation gas of $B_{10}H_{14}$ is led to the ionizer chamber, and ionized by an electron bombardment system. The ion beam intensity was controlled by the electron acceleration voltage (Ve), extraction voltage and ionizer acceleration voltage. After the ion beam is extracted, it is focused by lenses, and accelerated up to the proper acceleration voltage. The diameter

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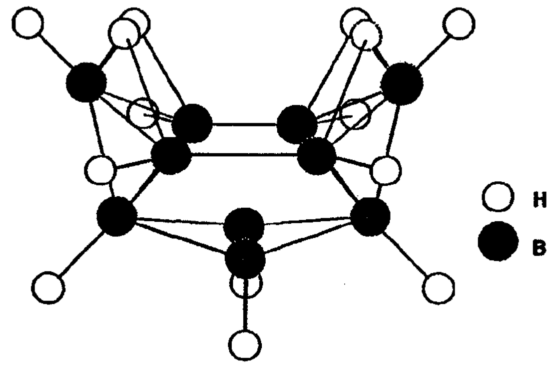

Fig.1. Structure of decaborane ($B_{10}H_{14}$)

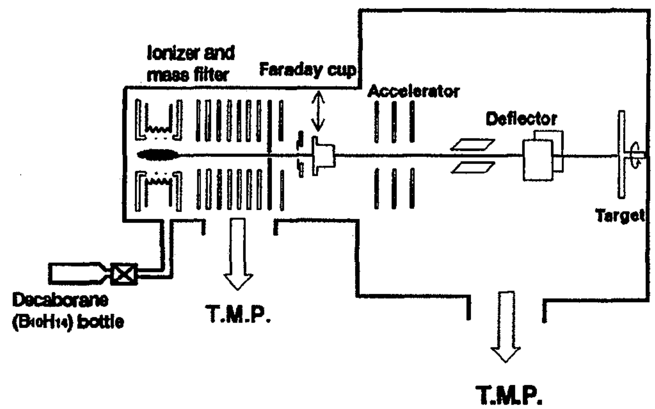

Fig.2. Schematic diagram of $B_{10}H_{14}$ implanter.

of the focused beam was 2mm. This spot is scanned by a deflector and irradiates the target.

III. Results and Discussions

Fig.3 shows a SIMS profile of B implanted into Si (100) by $B_{10}H_{14}$ implantation, for two values of Ve at a doses of 5×10^{14} ions/cm^2. The total acceleration voltage of the ions was 20kV. Ve was set to 60 and 150V, respectively. The total number of irradiated B atoms was 5×10^{15} atoms/cm^2, because a $B_{10}H_{14}$ ion has ten B atoms. The two SIMS profiles in fig.3 are normalized with the concentration at the surface in order to compare the implantation depth.

The number of implanted B atoms into Si (100) was 3.0×10^{15} atoms/cm^2 in the case of Ve=150V. Thus, the implantation efficiency was 60%. The implanted B reached to about 0.25 μm in depth.

When a $B_{10}H_{14}$ ion is accelerated to an energy E_0, the energy of one constituent B atom, E_{eq}, becomes

$$E_{eq} = E_0 \times (\frac{M_B}{M_{B_{10}H_{14}}})$$

where $M_{B_{10}H_{14}}$ is the molecular weight of $B_{10}H_{14}$ and M_B is that of the B atom. From this equation, E_{eq} is 0.089 times as large as E_0. Therefore, a B atom in $B_{10}H_{14}$, which is accelerated to 20kV, has an energy of 1.8keV. According to the above equation, it appears in the case of Ve=150V that $B_{10}H_{14}$ was cracked and the fragments were implanted with different velocities [8].

Fig.4 shows a SIMS profile of B atoms implanted into Si (100) by $B_{10}H_{14}$ implantation at a dose of 5×10^{14} ions/cm^2. Ve was set to 60V and the total acceleration voltage of ions was 20kV. This figure also includes a SIMS profile of B implanted into Si (100) by conventional B monomer-ion implantation, with and without pre-amorphization, at a dose of 1×10^{14} ions/cm^2. The B ions were accelerated up to 2kV. The scale of the concentration value for the information for $B_{10}H_{14}$ implantation was divided by 50, in order to compare with that for a single B one.

From fig.4, the efficiency of $B_{10}H_{14}$ implantation can be seem to be more than 90%, which is much higher than that in the case of Ve=150V. The range of the implanted B was about 0.1 μm. The depth profile in the case of $B_{10}H_{14}$ implantation looks almost the same, in range and shape, as that in the case of B.

These result show that the equivalent-low-energy effect of cluster ions, and that cracking of $B_{10}H_{14}$ was reduced when Ve=60V. On the other hand, by comparing the depth profile of B ion implantation with preamorphization, that of $B_{10}H_{14}$ shows channeling to deeper than 0.05 μm. This

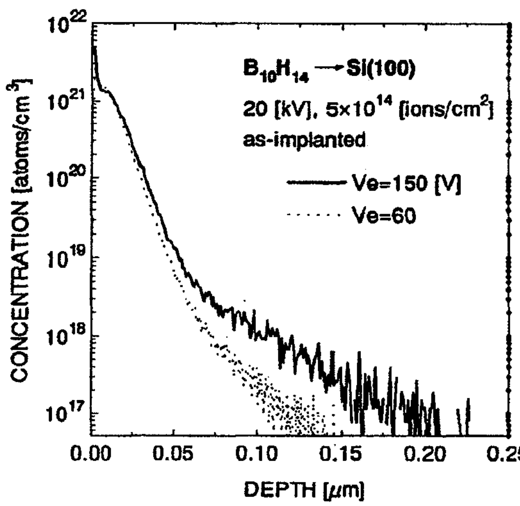

Fig.3. SIMS profile of B implanted into Si(100) at different electron acceleration voltage (Ve) conditions with a dose of 5×10^{14} ions/cm^2. The total number of irradiated B atoms was 5×10^{15} atoms/cm^2 because a $B_{10}H_{14}$ ion has ten B atoms. $B_{10}H_{14}$ was cracked at Ve=150V.

result is quite interesting from the view point of what is a cluster. From the results of molecular dynamics simulation, in the case of an Ar cluster has 13 atoms, the constituent atoms would not show channeling. On the other hand, in the case of B cluster which has same number of atoms, some of its constituent atoms show channeling effects. B is so much lighter than Ar that it cannot lose its energy immediately. In short, a B cluster of ten atoms cannot consume its energy in the shallow region next to the surface. Therefore, for the formation of a shallow junction less than 0.05 μm, it is necessary to use preamorphization, or to use larger sizes of B clusters, because a large cluster forms a local amorphous region in front of itself during penetration into solid, which can suppress channeling.

The implanted layer was annealed by a furnace in a N_2 atmosphere, or by rapid thermal annealing (RTA). Fig.5 shows a RBS channeling spectra of a Si (100) substrate implanted by $B_{10}H_{14}$ with a dose of 1×10^{14} ions/cm^2. Ve was set to 150V and $B_{10}H_{14}$ ions were accelerated up to 20kV. This figure includes spectra of an unirradiated Si (100) substrate, an as-implanted one and ones annealed at 600, 700, 800 and 900 °C for 30 minute.

It is seen from the spectrum of an as-implanted sample that the damage was obviously concentrated in a very shallow region. It, however, disappeared completely, even with low temperature annealing at 600 °C. This indicates that cluster implantation can form an amorphous layer completely, because cluster bombardment causes multiple-collisions and energy deposition in quite a local area. A single B ion can form an amorphous layer with a dose of more than 2×10^{16} ions/cm^2. $B_{10}H_{14}$, which is 11 times heavier than B, forms an amorphous layer with a dose which is one order of magnitude lower.

The total number of disordered atoms was obtained by integration over the surface-peak in the RBS channeling spectra [9]. The number of disordered atoms, due to cluster bombardment, increased with ion dose and finally reached saturation. This suggested that the modified layer was totally amorphized. The saturation numbers of disordered atoms were about 6.4×10^{16} atoms/cm^2. This corresponds to a depth of about 130Å.

In order to compare with the single B ion irradiation case, the number of disordered atoms were predicted using TRIM (Transport of Ions in Mater) [10] calculations. TRIM can be used to estimate the probability of vacancy production per ion.

By comparing experimental with calculated results, the number of disordered atoms created by one B atom in a $B_{10}H_{14}$ ions was the same as that caused by a B ion. This indicates that the $B_{10}H_{14}$ dose not have a non-linear effect [4,6], because at the moment when a $B_{10}H_{14}$ ion impacts the solid surface, it is broken into B atoms. One or two B atoms have enough energy to show channeling. This channeling was seen in fig.4. Therefore, it is necessary to use a much larger size of B cluster in order to reduce the channeling effect completely.

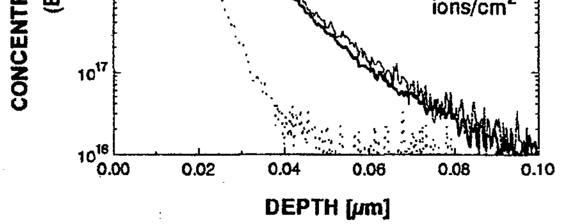

Fig.4. SIMS profiles of B implanted into Si(100) by $B_{10}H_{14}$ implantation, and of B implanted into Si(100) by conventional B ion implantation, with and without preamorphization. The concentration value for $B_{10}H_{14}$ implantation were divided by 50. The $B_{10}H_{14}$ ions were accelerated up to 20kV and B ions up to 2kV. The depth profile in the case of $B_{10}H_{14}$ implantation has almost the same range and shape as that in the case of B without preamorphization.

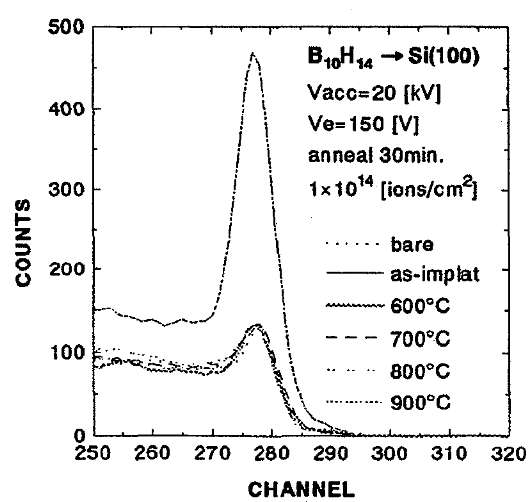

Fig.5. RBS channeling spectra of unirradiated, as-implantod, and annealed Si(100) substrates. Damage induced by $B_{10}H_{14}$ implantation was completely recovered even by 600 °C furnace annealing.

The resistivity of the implanted layer was measured using a four probe in order to study the electric activation. Fig.6 shows dependency of the sheet resistance upon the furnace anneal temperature. $B_{10}H_{14}$ was implanted at a dose of 5×10^{14} ions/cm^2. Thus the Si surface was amorphized. This results in electric activation even at 600 °C. The value of resistance, less than 1000 Ω/sq. by 20keV $B_{10}H_{14}$ implantation, at 600 °C can pass for the implantation of LDD (Lightly Doped Drain). Sheet resistance decreases to about 300 Ω/sq. at 900 °C.

This figure also shows a strong ion-energy dependency. However, the energy dependence appeared clearly at 600 °C, while it is not so strong at 900 °C. Because the implantation depths among these various energy implantation seems not to be different from one another so much, an agreement of the points at 900 °C in fig.6 is reasonable. The difference of resistance at 600 °C indicates that the damage caused by $B_{10}H_{14}$ implantation at 10keV is smaller than that by one at more than 20keV.

When implanted Si (100) was annealed by RTA at 900 °C, in the case of 5×10^{13} ions/cm^2 implanted into Si (100) at 20keV, the sheet resistance was 600Ω/sq. In order to estimate activation efficiency, the junction depth was set to 0.1μm, because transient diffusion of B is not enhanced by a 900 °C RTA for 10 sec. The surface concentration of B was set to 2×10^{20} atoms/cm^2 from the results of SIMS. Therefore the activation efficiency is 50%. In the case of 1000 °C, it became almost 100%.

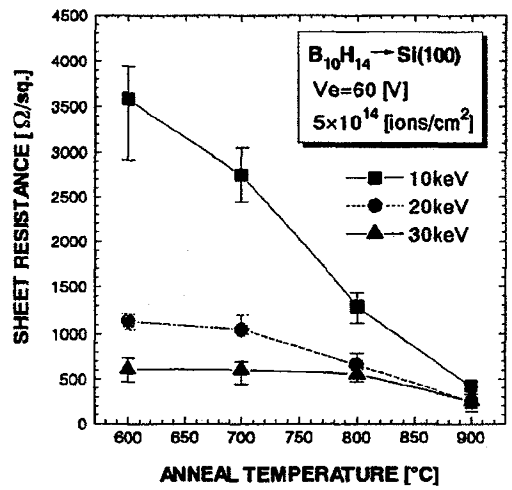

Fig.6. Dependency of the sheet resistance upon the furnace anneal temperature. $B_{10}H_{14}$ was implanted at a dose of 5×10^{14} [ions/cm^2]. Thus Si surface was amorphyzed. This results in electric activation even at 600 °C. This figure also depicted strong ion energy dependency.

IV. Conclusions

We have used a polyatomic molecule, decaborane ($B_{10}H_{14}$), as a kind of B cluster in order to form very shallow p^+ junction. A B SIMS profile of $B_{10}H_{14}$ implanted into Si(100) at 20keV is quite similar to that of B implanted at 2keV. The implantation efficiency achieved was about 90% and the implantation depth was less than 0.1μm. These results revealed that a cluster ion beam can realize equivalent low-energy implantation quite easily. On the other hand, the SIMS profile of $B_{10}H_{14}$ showed channeling. Additionally, RBS channeling methods revealed that the number of disordered Si atoms caused by $B_{10}H_{14}$ implantation was the same as that by B ion implantation at same atomic dose and ion velocity. This indicates that it is necessary to use the non-linear effect of larger clusters in order to reduce channeling.

Electric activation of implanted B was obtained by furnace annealing or RTA. Therefore it is appeared that cluster ion implantation has a great advantage as a technique for shallow junction formation.

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